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Simulation of Air Flow Through a Test Chamber

by Gregory K. Ovrebo

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14. ABSTRACT

Computer simulation was used to investigate the flow of forced air through a test chamber used to measure heat dissipated by an inductor. Cosmos FloWorks simulations provide a qualitative picture of the air stream passing through the chamber, as well as calculations of air velocity at the chamber outlet port. These results provide a correction factor for measurements of power dissipation in high-power electric components.

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Simulation, finite element, flow rate

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1. Introduction

The Army Research Laboratory (ARL) is interested in developing high power electronics for a range of Army applications. One aspect of this development effort is investigation of materials and designs which may optimize the operation of high-power inductors, an integral part of high-density power conversion systems. To this end, ARL scientists investigated inductor core designs using two different core materials and three different winding types[1].

Power loss in the test inductors was measured with a thermo-anemometer chamber. The inductor was placed inside an insulated chamber and operated as part of a DC-DC boost power-stage test fixture. Power levels were in the range of 5 to 25 kW. Air was forced into the inlet port with an attached blower. Air speed and air temperature were measured at the outlet port with a thermo-anemometer. This data, along with air specific heat and measurements of relative humidity and barometric pressure, were used to calculate air density inside the chamber and total power dissipation by the inductor. However, initial attempts at calculating inductor heating produced results which were anomalously high. It was determined that a simulation of air flow inside the thermo-anemometer chamber might resolve this anomaly.

2. Model and Simulation Preparation

A model of the thermo-anemometer chamber was prepared with SolidWorks modeling software. A view of the model, with its components rendered semi-transparent, is shown in figure 1. The box is 12 inches high, 12 inches wide and 18 inches long. Air flow enters the box through the round opening on the right, 3 inches in diameter, and exits through the port on the left. The exit port is extended with a tube in our model to allow some averaging of air velocity and avoid vertices at the exit, which can be computationally problematic. If we specify the velocity of air entering the chamber, we can calculate the flow properties, like velocity, pressure, and flow rate, through the box to the exit port. We used Cosmos FloWorks, a computational fluid dynamics software package, to perform these simulations.

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[1]Salem, T. E.; Urciuoli, D. P.; Lubomirsky, V; Ovrebo, G. K. Design Considerations for High Power Inductors in DC-DC Converters. *Applied Power Electronics Conference*, 2007.
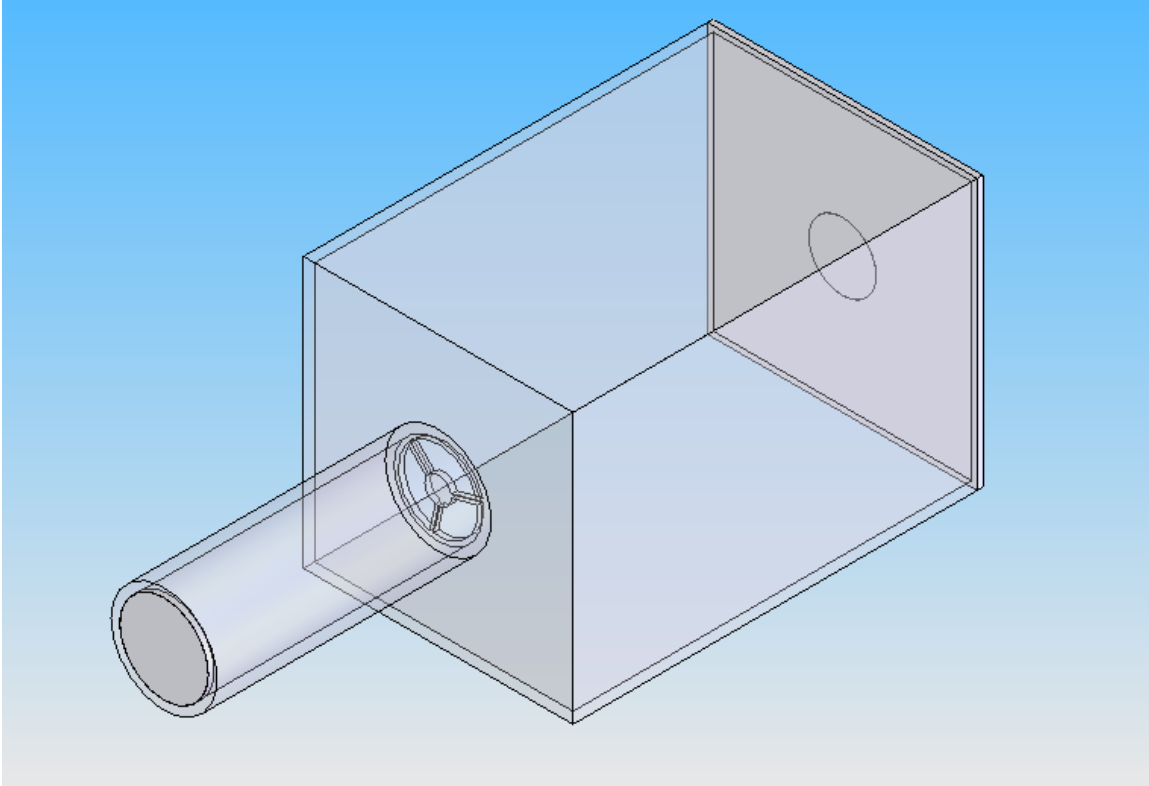
Figure 1. Solid model of a test apparatus which uses an anemometer and air temperature measurements to calculate power dissipation of an inductor inside the chamber.

3. Air Flow Simulation

Our simulation of air flow through the thermo-anemometer chamber began by defining a constant flow of air at 5.1 m/s into the 3-inch diameter inlet port. This simulates the blower attached to the test chamber inlet. The chamber model was meshed in Cosmos FloWorks with 48,000 cells. This is somewhat finer than the default mesh, avoiding computational anomalies encountered in preliminary simulation attempts while still keeping run times manageable. The solid model was modified for each run, changing the diameter of the outlet port so we could study the effect of outlet size on the air velocity coming out of the box. Outlet diameter was varied from 2 inches up to 4 inches. A chart of average air velocity at the exit as a function of outlet diameter is shown in figure 2.

The source of the experimenters' quandary can be seen in this figure. Contrary to what one might assume, the speed of the air leaving the chamber is greater than the speed of the air entering it, even when inlet and outlet ports are the same size. Although the inlet air velocity is

5.1 m/s, the outlet velocity from an identical 3-inch port is 7 m/s. The simulation results can shed some light on what is happening to the air flow inside our chamber.
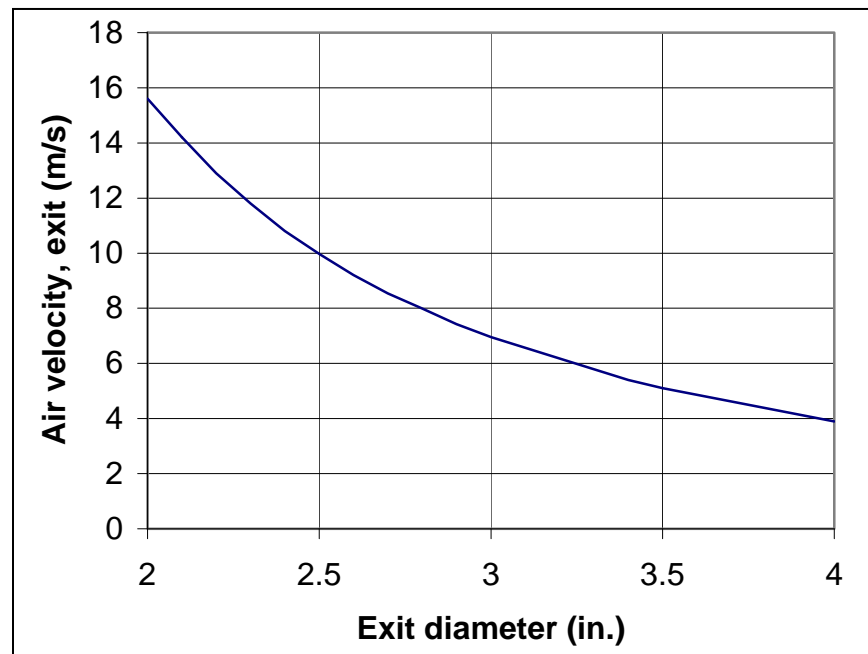

Figure 2.   Velocity of air leaving the thermo-anemometer chamber, as a function
of outlet port diameter.

Figure 3 is a side view of air flow through the center of the chamber, where the trajectories shown represent sampled air streams inside the box. The colors denote the velocity of the air streams as they pass from the inlet, on the right side of the chamber, to the outlet, on the left side. In this example, the inlet and outlet ports are both 3 inches in diameter. Note how the envelope of the air flow spreads as it travels down the box, and then narrows again at the outlet.
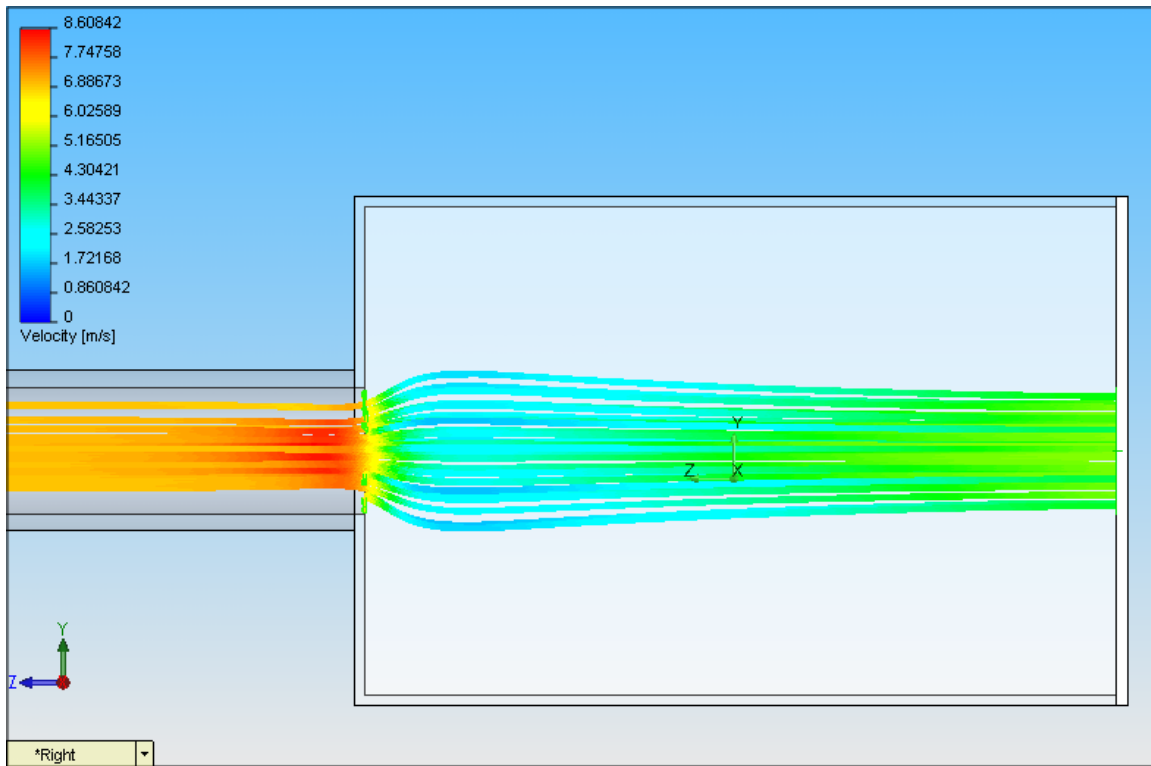
Figure 3. Sampled air flow trajectories passing through the box. Side view of the center plane.

Figure 4 is the same side view of the center plane of the chamber, showing a contour plot of air velocity inside the box. Again we see the spreading of the air stream traveling through the box, narrowing as it reaches the exit. Also note how air speed increases at the outlet in a sort of Bernoulli effect.
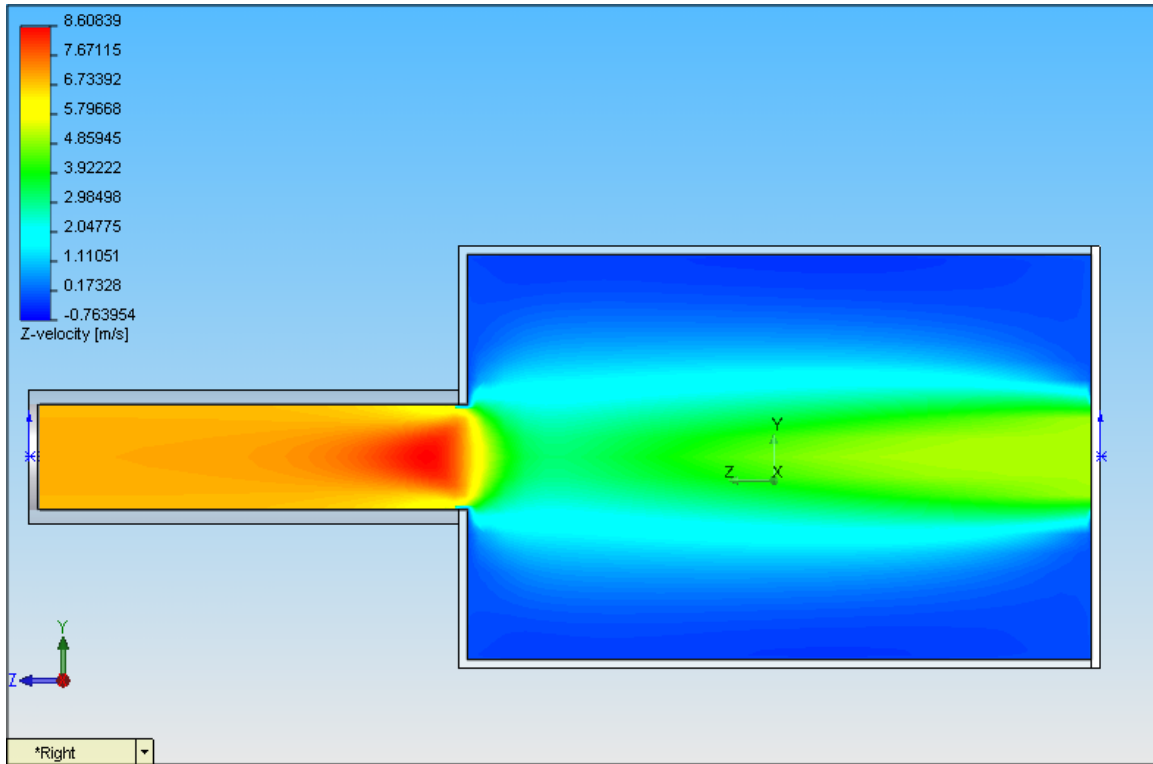
Figure 4. Contour plot of air velocity inside the box. Side view of the center plane.

In figure 5 we look at a close-up view of the outlet port of the thermo-anemometer chamber. One factor in the discrepancy between inlet and outlet air speeds is laminar flow at the outlet, where air velocity at the port's surface is zero, and increases farther from the surface. In the contour plot, this laminar flow is represented by a dark blue region next to the opening. This means that the outlet port's effective size is smaller than the measured diameter.
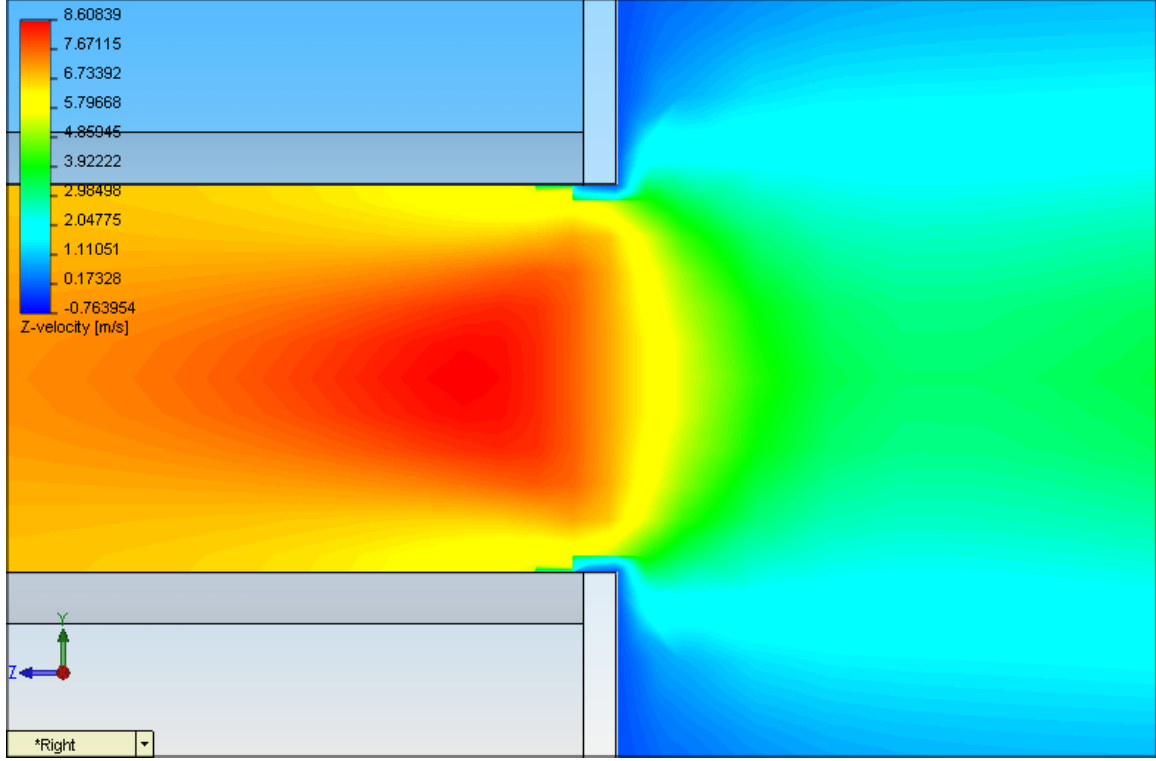
Figure 5. Laminar flow at the edges of the outlet reduces the effective diameter of the port.

4. Results

Our investigators calculated the power P dissipated by the inductor inside the thermo-anemometer chamber with the formula[2]

$$P = D_a \cdot A \cdot v \cdot C_p^1 \cdot \Delta t,$$

where the air density D_a is derived from the formula[3]

$$D_a = \frac{[3.4844p - h(2.52t - 20.582)]}{t + 273.15}.$$

A = air outlet cross-sectional area,

C_p^1 = air specific heat with humidity at standard pressure,

h = relative humidity,

[2]Wong, G.S.K.; Embleton, T.F.W. Variation of Specific Heats and of Specific Heat Ratio in Air with Humidity. *Journal of the Acoustical Society of America* **Aug. 1984**, 555–559.

[3]Journal of Research of the National Bureau of Standards (U. S.), 1978, 83, 419.

p = barometric pressure,

t = air inlet temperature,

Δt = air outlet temperature rise,

and   *v* = air outlet speed.

A correction to *A*, the air outlet cross-sectional area, had to be made to account for the laminar flow around the surface of the outlet. According to the results of our fluid dynamic calculations performed with Cosmos FloWorks, outlet air velocity equals inlet air velocity in our chamber when the outlet is 3.5" in diameter, compared to the inlet's 3.0" diameter (see figure 2). This ratio of 3.0/3.5, or 0.857, will correct for the anomaly observed in power measurements due to the properties of air flow in the thermo-anemometer chamber.

5.   Conclusion

We were able to resolve an anomaly in the experimenters' calculations of power dissipation by high power inductors. The analysis of the behavior of air flow inside their experimental apparatus revealed laminar flow around the outlet port of their thermo-anemometer chamber. A correction factor was calculated to account for the effective diameter of the outlet port and correct the calculation of power dissipated by the inductor.

This use of a fluid dynamics computation allowed a quick resolution of a problem which did not lend itself to an analytic solution, and which might have required much more time and resources to be resolved empirically.

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